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Diagnosis of bearing creep in wind turbine gearboxes

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ABSTRACT

One of the most wide spread gearbox topologies in the wind energy sector consists of a slow rotating planetary stage, an intermediate speed parallel stage and finally a high speed parallel stage driving the generator rotor. The shafts of the two latter stages are supported by ball or roller bearings where their outer races are fixed to the gearbox and their inner races rotate at the corresponding shaft speed. Bearing inner race defects are frequently encountered in gearboxes leading to either replacement of the whole unit or exchange of the shaft or bearing where feasible. The present work deals with the evaluation of the development of an inner race defect from surface pitting to race axial crack resulting in excessive rotational looseness, also referred to as bearing creep. It is shown that an inner race defect can be identified efficiently at an early stage by employing well known vibration condition indicators, e.g. crest factor, whereas development to rotational looseness is expressed as increased sideband activity between the gear mesh frequencies spaced at the shaft speed supported by the defective bearing due to abnormal meshing. The condition of the gears and the shaft during the final stage of the above described failure mode is essential in regards to the possibility of uptower repairs or their use in refurbished gearboxes. Case studies from operating multi-megawatt wind turbines are presented, illustrating the progression of the fault via continuous trending of condition indicators and detailed spectral analysis of high resolution vibration signals.

1. INTRODUCTION

Although many wind turbine manufacturers have introduced direct drive wind turbines, especially for offshore installations, geared turbines occupy large percentage of the already existing and future projects. A long established gearbox topology for wind turbine below 2.0MW incorporates three stages, i.e. a slow rotating planetary (epicyclic) stage, an intermediate speed parallel stage and a high speed parallel stage. In turbines of rating higher than 2.0MW, the intermediate stage is usually epicyclic due to the higher torque load capacity and higher ratio in a compound configuration (Oyague, 2009).

Detection of gear and bearing defects in wind turbines has drawn wide attention from the academic community and industry sector over the past decades employing various techniques, e.g. vibration acoustic emission and oil analysis (Dempsey & Sheng, 2013), (Qu et al., 2014), (Zhang, Verma, & Kusiak, 2012), (Feng, Qiu, Crabtree, Long, & Tavner, 2013). Vibration monitoring systems are commonly met in megawatt class wind turbines where accelerometers are mounted on the drive train offering consistent and reliable indications in regards to the health of the corresponding components. Numerous signal processing techniques in the time, frequency or time-frequency domains, such as envelope analysis, spectral kurtosis, time synchronous averaging and wavelet transformation, have been vastly exploited in detection of faults in gearboxes (Siegel, Zhao, Lapira, AbuAli, & Lee, 2014). Although the focus of many researchers has been concentrated on planetary slow rotating stage faults, mainly due to their challenging nature and detection complexity (Hong, Dhupia, & Sheng, 2014), it is of equal importance to evaluate defects in parallel stages accurately, as uptower repairs could be performed minimizing the required downtime and repair expenses.

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A typical installation on a drive train consisting of two main bearings, gearbox and generator usually includes eight to ten accelerometers, where four to six sensors are placed on strategic positions on the gearbox housing ensuring optimum transmission path between them and the rotating parts of interest. On-line vibration based condition monitoring systems facilitate two interconnected procedures (Skrimpas, Marhadi, Jensen, et al., 2015). Firstly, scalar values of extracted condition indicators (CIs) are utilized for alarming, long time trending and preliminary severity assessment. There is an arsenal of CIs applied in analysis of gearbox failures aiming at early detection on one hand and reliable prognosis of the useful remaining lifetime on the other hand (Zhu, Nostrand, Spiegel, & Morton, 2014). These two objectives are usually contradictory, therefore it is common to employ multiple indicators per monitored component. The second stage incorporates fault detection and remaining useful lifetime evaluation based on detailed analysis of high resolution signals aiming at localization of the failed subcomponent and examination of historical vibration trends. The human factor is typically introduced for final decision making.

The current work deals with diagnosis and prognosis of rotational looseness, also referred as to creep, in gearbox intermediate stage shaft bearings originated by inner race cracks, a failure mode which has not received any attention from the scientific community based on the authors' knowledge. Two condition indicators are utilized, namely the high frequency crest factor (HFCF) and residual value (RV), which provide indications in early and late stage of the failure mode respectively. A case study is presented, showing the development of the fault of interest based on trends and detailed spectral analysis.

The rest of the paper is organized as follows: the failure mode of interest is discussed in section 2. Section 3 presents the way of collecting and preprocessing data in modern condition systems. The utilized signal processing techniques are briefly presented in section 4. The two condition indicators based on which the faults are detected and estimated are examined in section 5. A case study of a wind turbine subjected to gearbox bearing creep is reviewed in section 6. Finally sections 8 and 9 present the discussion and conclusions respectively.

2. FAILURE MODE DESCRIPTION

Gearbox bearings suffer from all typical failures, such as inner or outer race defects, where the severity, development rate and frequency depends on various factors, such as applied load, i.e. radial or axial-radial, design of gearbox and position of the bearing. In this work, a special failure mode seen mainly in the inner raceway of roller bearings is investigated and analysed. The fault development is assessed to follow the stages depicted in Figure 1, where it is assumed that it commences in the form of pitting in early stage, al-

though the latter cannot be verified due to lack of inspections at this stage. Typically, this failure mode develops to hair line cracks in mid-early stage, where more than one cracks might be present, and propagates to extensive crack and spalling in mid-late stage. The final stage is a combination of severe bearing damage and rotational looseness, i.e. bearing creep, due to loose fit between the shaft and the inner race. The exact nature of rotational looseness cannot be explicitly verified, i.e. if the relative motion between the shaft and the inner race can be characterized as micro or macro movement. However, based on the extent of wear on the shaft surface, it is believed that it is most likely macro-movement either intermittent or continuous, depending on the applied load. The latter can be confirmed if the data are classified in torque or power bins, as it is shown in latter section.

Spinning of the inner race on the shaft results in extensive shaft wear, which requires replacement of the whole shaft. In addition, the meshing between the gear(s) mounted on the affected shaft and the corresponding gear of the same stage, either pinion or gearwheel, deviates from the normal operational condition due to the developing looseness, jeopardizing the teeth profile and general health of the entire gearbox. If the fault is detected and troubleshot in early-mid stage, the faulty condition can be handled successfully by replacing solely the bearing, minimizing the down time and cost of repair.

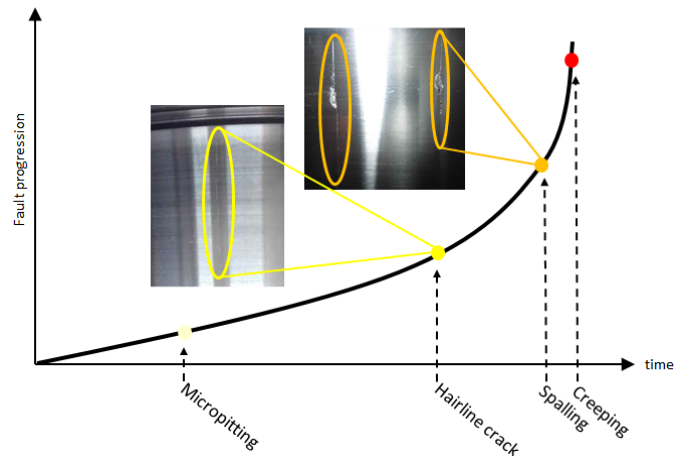


Figure 1. Stages of the failure mode under investigation.

Figure 2 illustrates all bearings and gears of a typical modular drive train configuration. Although it can be encountered in any bearing supporting either the low, intermediate or high speed shafts, it is most commonly seen in roller bearings.

A crucial aspect in the consistent evaluation of this failure mode is the time interval between the detection of the fault at an early stage until it reaches the state of creeping on the shaft. By analysing ten faults from one wind park with identical gearbox types in order to have a homogeneous sample, it

has been concluded that this period does not follow a specific distribution, but it ranges from a few weeks to approximately 10 months. Data from replaced bearings before creeping has taken place suggests that the remaining lifetime might exceed one year after the fault is detected, providing long lead time to the service organization for ordering the spare parts, planning and performing the replacement effectively with minimum cost.

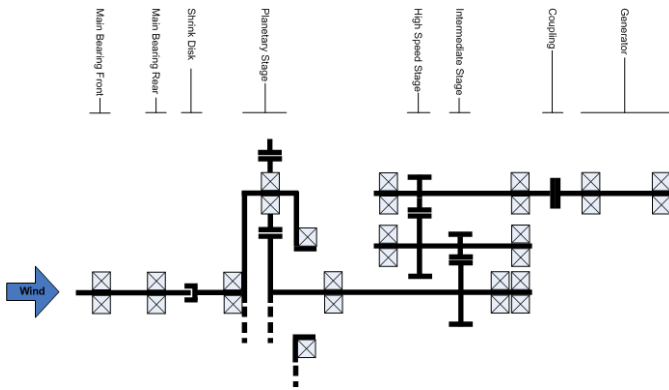


Figure 2. Gear and bearing locations in a three stage (one planetary and two parallel) gearbox, along with two main bearings and generator bearings.

3. DATA ACQUISITION

Figure 3 illustrates the positioning of accelerometers across the drive train, marked with red rings. It can be seen that their positioning is selected strategically in order to ensure optimum vibration path between the monitored component and the sensor. Furthermore, speed signal is commonly included in most condition monitoring systems (CMS), providing the reference for speed related measurements. In Figure 3 the tachometer is represented by a blue ring on the gearbox high speed shaft.

All vibration signals are collected by a data acquisition (DAQ) unit along with inputs from other units, such as the turbine controller. Typical readings are temperature values from main bearing, gearbox and generator bearings, and operational values, e.g. wind speed and power production. Depending on the applied monitoring strategy of each CMS provider, the DAQ unit may serve as first level processor, where various CIs are calculated continuously and streamed to a server in predefined time intervals, usually between ten minutes and one hour. The main advantages of utilising the DAQ unit as preliminary CI calculator is the distribution of computational power to multiple systems rather than just a centralized server. The above becomes more critical with increasing number of monitored wind turbines. Furthermore, the frequency of receiving data can be set down to a few minutes as only scalar values are pushed corresponding to a few

kilobytes, whereas acquisition of time waveforms even every few hours would require massive storage capacity.

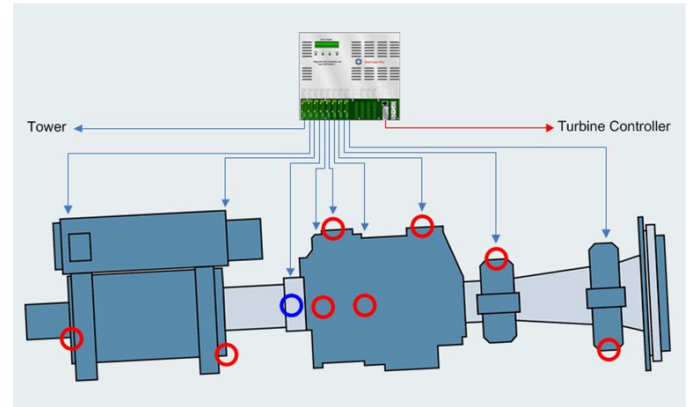


Figure 3. Layout of installed sensors, accelerometers in red and tachometer in blue, in a typical wind turbine drive train.

4. SIGNAL PROCESSING TECHNIQUES

Employment of sophisticated signal processing techniques on fault detection, such as wavelet analysis, has been suggested by numerous researchers in order to diagnose bearing and gear faults (El Morsy & Achtenová, 2015). Besides the computational demands, especially for the methods applicable in the time-frequency domain, the relative complexity of interpretation and visualization of the data are factors that prevent CMS companies to exploit them in large scale, or to a certain extent not use them as reference when communicating their findings to the service providers.

In this work, Fourier Transform and envelope analysis are used to display the presence of defect frequencies. The main drawback of these methods in analysis of vibration signals from wind turbines is their non-stationary nature due to speed variation. One of the most effective techniques to overcome this issue is resampling the signal in the angle domain with an equal phase increment of a selected shaft (Villa, Reñones, Perán, & De Miguel, 2011). Although the frequency and envelope spectra presented in the following sections are acquired under almost constant speed (less than 0.5% variation), and thus no resampling is performed, this method is extensively used in modern signal analysis software packages.

Derivation of the envelope signal is performed using the process displayed in Figure 4 (Skrimpas, Marhadi, Gomez, et al., 2015). Following the block diagram, the raw signal passes through a bandpass filter of predefined bandwidth, usually of lower cut-off frequency close to 1-2kHz in order to suppress strong spectral components from the high speed stage. The filtered signal is then rectified, shown as a diode, resulting in a unipolar signal. Finally, a low pass filter is applied in order to compute the envelope signal, where its cut-off frequency

is selected to be half of the above mentioned lower frequency of the bandpass filter.

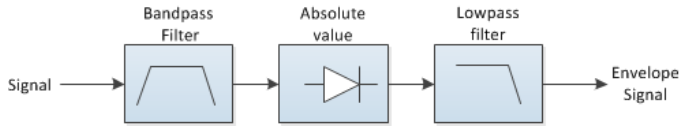


Figure 4. Process of envelope signal calculation.

5. VIBRATION BASED CONDITION INDICATORS

One of the most essential parts of a successful condition monitoring system is the employment of effective and reliable condition indicators. Effectiveness is related to the capability of the CI to track a fault at early stage, offering the desired lead time to inspection and troubleshooting. However, in order to cover a wide range of faults, CMS providers exploit multiple CIs with varying sensitivity to fault types and severity. For example, signs of early stage bearing faults are present in the high frequency bands, usually seen more efficiently using enveloping techniques, whereas propagation to mid-late stage results in the direct presence of discrete spectral components in low frequencies, e.g. below 1kHz. Minimization of false alarms is of equal importance to effectiveness when a CI is used, depicting its level of reliability. The latter carries more weight with increasing numbers of monitoring systems adding extra, unnecessary workload to the engineers evaluating different types of faults. Furthermore, false diagnosis could lead to needless visits to wind turbines or even redundant attempts of fault mitigation, diminishing the value of CMS in the condition-based maintenance.

In the current work, two condition indicators are used in order to detect and evaluate the presence of gearbox bearing inner race cracks and creep at early and late stage respectively. The first feature is referred to as High Frequency Crest Factor abbreviated as HFCF, which is an early stage fault indicator equal to the ratio between the peak and rms values in the high frequency range, typically over 1kHz, as shown in equation 1.

$$HFCF = \frac{Peak}{RMS} \quad (1)$$

Alternatively to HFCF, both peak and rms values could be utilized; however, it is found that HFCF offers the most representative status of the failure mode described in section 2.

Residual signals in vibration based condition monitoring are calculated by removing the expected gear mesh frequencies and taking into account the sidebands and noise between them. Alternatively, if the first sidebands are also discarded, the signals are referred to as differential signals (Zhu et al., 2014). In the current application, the residual value (RV),

which is the energy of the spectral content between the first three gear mesh frequencies, is considered.

$$RV = MESH - \sum_{i=1}^3 TMF_i \quad (2)$$

where MESH is the energy of the signal from below the first up to the third tooth mesh frequency.

It is noted that both CIs are sensitive to a large variety of faults, as for example HFCF responds under any bearing associated defect, not only inner race faults. Similarly, RV is the most reliable indicator regarding gear issues, e.g. broken or cracked teeth, improper meshing, excessive wear, etc. However, in this work it is the combined evaluation of the two CIs which results in the accurate and consistent detection of bearing inner race creep.

6. CASE STUDY

A defect in one of the intermediate shaft support bearings following the stages of the failure mode of interest, i.e. axial crack, spalling and creeping, is discussed and analysed. The analysis part is based on both scalar values from selected condition indicators, and detailed analysis of high sampled vibration signals recorded by the accelerometer installed adjacent to the intermediate stage (2nd stage). It is important to highlight the fact that all scalar values are classified in five discrete power bins offering enhanced fault detectability capabilities and consistent comparison between different operational states.

Figure 5 illustrates the high frequency crest factor trending behavior in high power production extracted from the accelerometer installed adjacent to the intermediate stage (2nd stage). In details, HFCF started increasing in July 2013 and crossed a predefined alert limit after approximately one month, where the defect is assessed to be at early stage. Based on the applied condition monitoring strategy, this is the first generated alarm by the system which requires further evaluation from specialists. It is noted that the lower alert limit, represented by a yellow horizontal coloured line, is configured by the system using basic statistical features, such as mean value and standard deviation, from a predefined time interval where the condition is assessed to be fault free. On the contrary, the red line, referred to as danger line, is fixed for all turbines of the same platform. The HFCF trend continues to progress until October 2014 where it stabilizes at a new level approximately twice the value at the healthy state period. Based in Figure 1, the most likely stage of the defect is between hairline crack and spalling in the inner race.

Spectral analysis validates the presence of an inner race defect as displayed in Figure 6, which presents the envelope spectrum from the signal collected by the accelerometer ded-

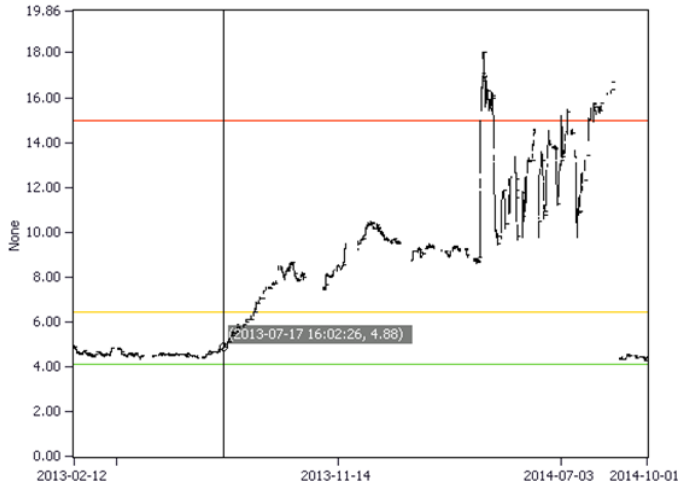


Figure 5. Trending behaviour of HFCF over a period of approximately 18 months in high power production.

icated to the intermediate stage of the gearbox. Multiple harmonics of the inner race defect frequency (BPFI - ball pass frequency inner) along with sidebands matching the running speed of the shaft supported by the bearing can be located, pinpointing the defective bearing and the exact location of the fault.

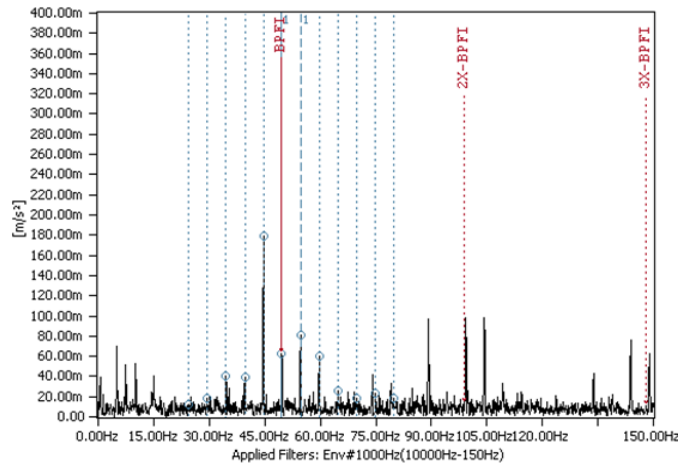


Figure 6. Envelope spectrum after the rise of HFCF, but before RV step change.

Figure 7 shows the frequency spectrum focusing on the bandwidth close to the first three tooth mesh frequencies of the 2nd stage. Detailed analysis does not reveal any signs of potential faults, such as increased sidebands, hence at this stage the fault is reckoned as early stage and does not influence the meshing of the gears.

Consistent diagnosis of the final state of the described failure mode, i.e. bearing creep, is achieved effectively by inspecting the RV trends for sudden step changes. It is important to emphasize the fact that by comparing multiple failed bearings,

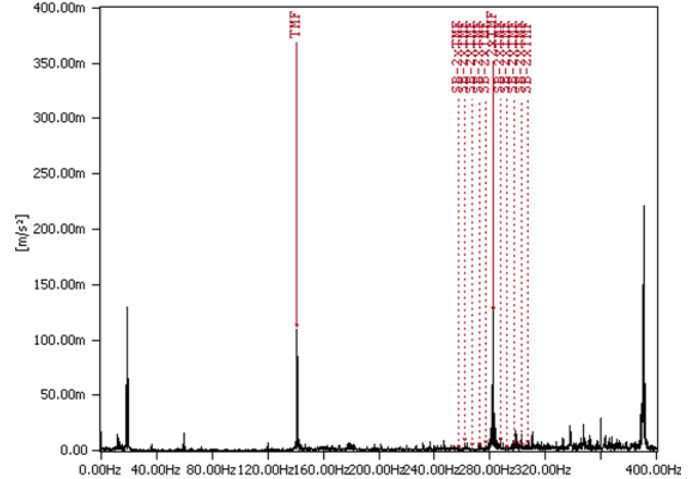


Figure 7. Frequency spectrum after the rise of HFCF, but before RV step change.

the authors have verified that RV changes rapidly within a few hours and stabilizes at a new level. This behaviour suggests that the axial crack escalates rapidly to broken inner race or at least to such an extent which allows the bearing to move relative to the shaft due to loss of interference fit.



Figure 8. Trending behaviour of residual value (RV) over a period of approximately 18 months in high power production.

The emerging looseness affects the load on the gears resulting in abnormal meshing. The latter propagates in the frequency spectrum in the form of multiple sidebands around the tooth mesh frequencies matching the running speed of the shaft supported by the failed bearing. Figure 9 illustrates the frequency spectrum of a recorded signal after the RV step change where multiple sidebands are present. Furthermore, a similar step change is observed in the HFCF trends in Figure 5 indicating that the impacts are now higher in amplitude most probably due to a larger crack. This effect can be confirmed in the envelope spectrum in Figure 10 where the char-

acteristic inner race defect frequency and its sidebands are more pronounced compared to Figure 6.

The gearbox was kept in operation for approximately 40 days after the RV sudden increase resulting in extensive damage of the intermediate shaft. It is noted that the present case study is one of the first subjected to this failure analysed by the authors, hence this time interval is not representative for gearboxes suffered from the same fault. However, it can be argued that further running could potentially jeopardise the condition of the gears.

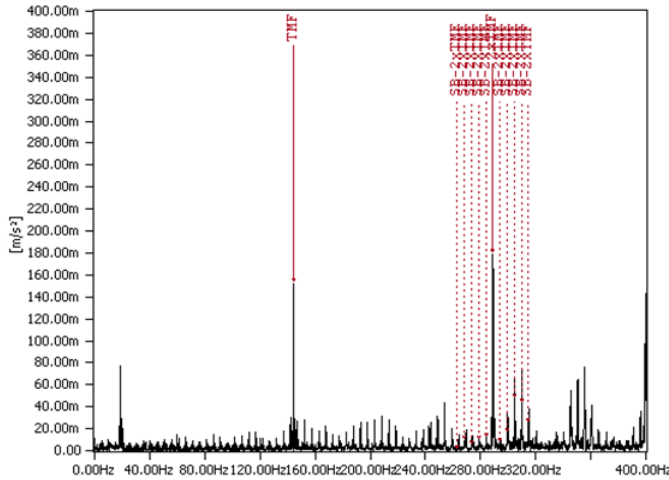


Figure 9. Frequency spectrum after the step change of RV.

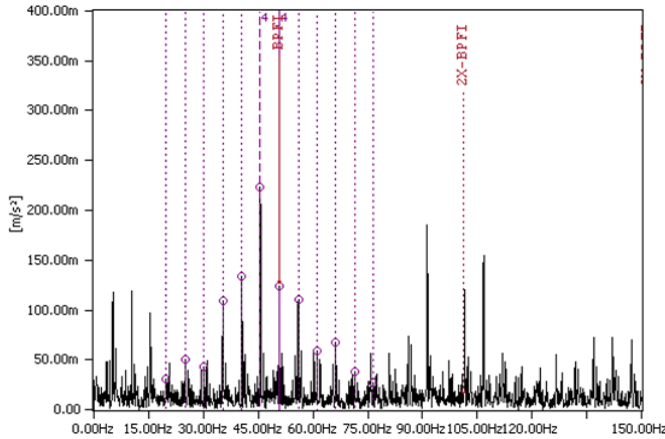


Figure 10. Envelope spectrum after the step change of RV.

7. STATISTICAL ANALYSIS OF REMAINING USEFUL LIFETIME

In order to investigate the fault progression rate and the time interval for a defect to escalate from inner race spalling to creep, 18 cases of faults at the same location of the same gearbox type are analysed. Figure 11 shows the probability density function of the faults under consideration, which

ranges from a few days to approximately 20 months. The underlying distribution can be represented by a Weibull distribution shown with red in Figure 11 with $\alpha = 1.013$ and $b = 198.755$, based on Equation 3. Figure 12 displays graphically if the data are originated from Weibull distribution, using the Matlab built-in function *wblplot()*, which is assessed to be valid due to the linear relationship.

$$f(x|\alpha, b) = \frac{b}{\alpha} \left(\frac{x}{\alpha}\right)^{b-1} e^{-(x/\alpha)^b} \quad (3)$$

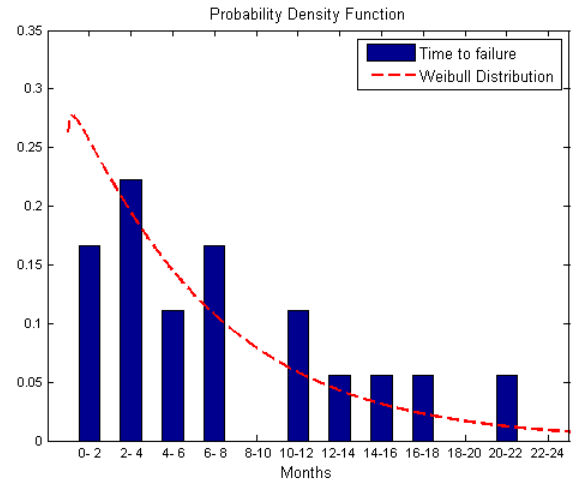


Figure 11. Probability density function of remaining useful lifetime for the failure mode of interest.

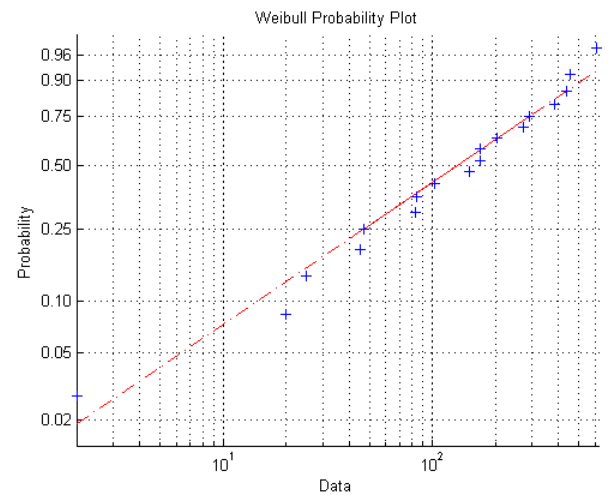


Figure 12. Assessment if data are originated from Weibull distribution.

8. DISCUSSION

The current work highlights the need for combined utilization of different condition indicators in the evaluation of gear-

box bearing creep, which should be also inferred to all failure modes in order to estimate the fault severity and component remaining useful lifetime consistently. Exploitation of the most reliable and consistent CIs is crucial when monitoring hundreds or thousands wind turbines and should get the highest priority from all stakeholders in the field of CMS.

As in many cases, it is unfortunate that at least one catastrophic failure is needed in order to formulate proper understanding of the failure mode and the response of the employed condition indicators or even realize that new CIs need to be introduced to detect it accurately. Fine tuning of alert limits for existing measurements or installation of extra sensors are also options that could add high value to CMS and condition-based maintenance in general.

9. CONCLUSIONS

The current study shows the diagnosis and prognosis principles of identifying consistently the presence of rotational looseness in gearbox parallel shaft support bearings, originated from hairline cracks on the inner race. Two conditions indicators, high frequency crest factor and residual value, are discussed which represent the two phases of the failure mode and thus serving as reliable prognostic descriptors. Detailed spectral analysis is essential part in localizing the faulty sub-component, where the envelope spectrum is utilized in the early stage to pinpoint the inner race characteristic fault frequency, and the frequency spectrum shows clearly the increased sidebands as result of the improper meshing of the intermediate stage gears due to bearing creep. Finally, from a statistical standpoint, the remaining useful lifetime of the component from the moment the fault is detected until it propagates to very late stage, i.e. bearing creep, follows a Weibull distribution.

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BIOGRAPHIES

Georgios Alexandros Skrimpas received the Diploma in electrical and computer engineering from the Aristotle University of Thessaloniki, Greece, in 2009 and the M. Sc. in wind energy from the Technical University of Denmark (DTU) in 2012. He joined Brüel and Kjær Vibro in 2012 and since 2013 he is pursuing the Industrial Ph.D. degree at the Centre of Electric Power and Energy at DTU in cooperation with Brüel and Kjær Vibro. His research interests are diagnosis and prognosis of electrical and mechanical faults in wind turbines.

Zhenyan Liu is a diagnostic engineer in the Remote Monitoring Group at Brüel and Kjær Vibro. She joined Brüel and Kjær Vibro in Oct, 2010. Previously, she worked in Vattenfall as a mechanical engineer. She received her M.Sc. degree in Wind Energy at the Technical University of Denmark (DTU) and B.Sc. degree in Mechanical Engineering from Shandong Jiaotong University, China. Her expertise is in structural vibration and analyses, probabilistic methods, and data mining.

Reynir Hilmisson received the B.Sc. and M.Sc. degrees in Electrical Engineering and Acoustics from the Technical University of Denmark in 2007 and 2009. Since 2009 he has been with Brüel and Kjær Vibro as Diagnostic Engineer. Prior to joining Brüel and Kjær Vibro, he was an Acoustic Engineer

for Tymphany Company and Electrical Engineer Intern for APC. He holds an ISO Level 3 certification in vibration diagnostics. His research interests are in development and implementation of condition monitoring solutions specific to wind power generation.

Christian Walsted Sweeney received his B.Sc. degree from the University of Southern Denmark in 2006 and M.Sc degree from the Technical University of Denmark in 2008 both in mechanical engineering. From 2008 to 2010 he was employed by Brüel and Kjær Vibro as diagnostic engineer and since 2010 he is the team leader of the diagnostic services group. His research focus is on the development of condition monitoring systems and handling of large data quantities.

Joachim Holboell is associate professor and deputy head of center at DTU, Department of Electrical Engineering, Center for Electric Power and Energy. His main field of research is high voltage components, their properties, condition and broad band performance, including insulation systems performance under AC, DC and transients. Focus is also on wind turbine technology and future power grid applications of components. J. Holboell is Senior Member of IEEE.